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RADC-TR-76-286, Vol II (of two)
Final Technical Report
September 1976

ROME AIR DEVELOPMENT CENTER

ADVANCED TRANSDUCER TECHNOLOGY
Survey of Transducers for Physical Security Sensors

Southwest Research Institute

AD A032316

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This report documents the results of a survey aimed at the identification and evaluation of new materials or techniques which could potentially advance the state-of-the-art in intrusion detection and perimeter surveillance systems. The emphasis here is not on complete systems but is concerned for the most part with the transduction phenomena, that is, the conversion of some intrusion generated disturbances into an output signal. The targets of interest in considering sensors or transduction phenomena are vehicles and humans. The pri- over

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mary types of transducers which have been employed for the detection of these disturbances have been seismic, acoustic, magnetic, electromagnetic, infrared, pressure and ultrasonic sensors.

The sources (1971-1976) used in searching for new developments included the International Aerospace Abstracts, Engineering Index, Scientific and Technical Aerospace Reports, STAR, Science Abstracts, Electrical and Electronics Abstracts, DDC computer search and other miscellaneous documents. Most of the papers selected for review and those which are reported in this document are refinements of previous types of detectors using new fabrication techniques, lower cost, improved ruggedness, lower power consumption, higher sensitivity or increased bandwidth. Areas discussed were concentrated on acoustic, magnetic, electromagnetic, infrared and pressure transducers.

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EVALUATION

This work identifies new material and techniques which could potentially advance the state-of-the-art in physical security sensors. The information developed will provide a baseline for continued exploitation of concepts to improve the detection capabilities of physical security sensors in support of the Base and Installation Security System Program.

Robert B. Curtis

ROBERT B. CURTIS
Project Engineer

I. INTRODUCTION

The objective of this report is to document the results of a survey aimed at the identification and evaluation of new materials or techniques which could potentially advance the state-of-the-art in intrusion detection and perimeter surveillance systems. The emphasis here is not on complete systems but is concerned for the most part with the transduction phenomena, that is, the conversion of some intrusion generated disturbances into an output signal. Certainly such signals may be further conditioned by the use of sophisticated electronic processing to extract intelligence, but this aspect of such instrumentation systems is outside the scope of this work.

Intrusion detection and perimeter surveillance systems have been under development and applied by the military for more than fifteen years. The ground sensors used in these applications have been used primarily in fixed installations security systems. The ways in which the sensors are used in either the point or line forms are:

- Penetration Sensors - those detecting penetration or attempted penetration through the boundaries of an installation perimeter or into high value storage areas within the perimeter.
- Volumetric Sensors - those detecting the presence of an intruder within buildings or other selected volumes.
- Transient Property Sensors - used to protect high value targets such as parked aircraft.
- Remote Sensors - used for the surveillance of unattended sites.

The earliest of the intrusion detection systems were passive line or point sensors utilizing conventional transducers (geophones, microphones photoelectric devices, etc.) and simplified electronic designs. These systems performed well under idealized conditions but were, in general, very sensitive to false disturbances. In the late 1960's, sophisticated signal processors were developed and used to extract target signal signatures to discriminate intrusion events from false alarms. These first efforts at signal processing were developed using available sensors. More recently, however, some effort has been directed towards the refinement of the target detecting transducers and developing new and improved transducer technology.

The targets of interest are, for the most part, vehicles and humans. The signatures of interest generated by the two types of sources are often marked by background noise coming from both cultural and natural

sources. The primary types of transducers which have been employed for the detection of the intrusion generated signals are seismic, acoustic, magnetic, electromagnetic, infrared, pressure, and ultrasonic sensors. This study is aimed at finding advances in the state-of-the-art for transducers of these phenomena. Of interest are new materials, new fabrication techniques, cost, ruggedness, power consumption, sensitivity, and bandwidth.

II. TECHNICAL DISCUSSION

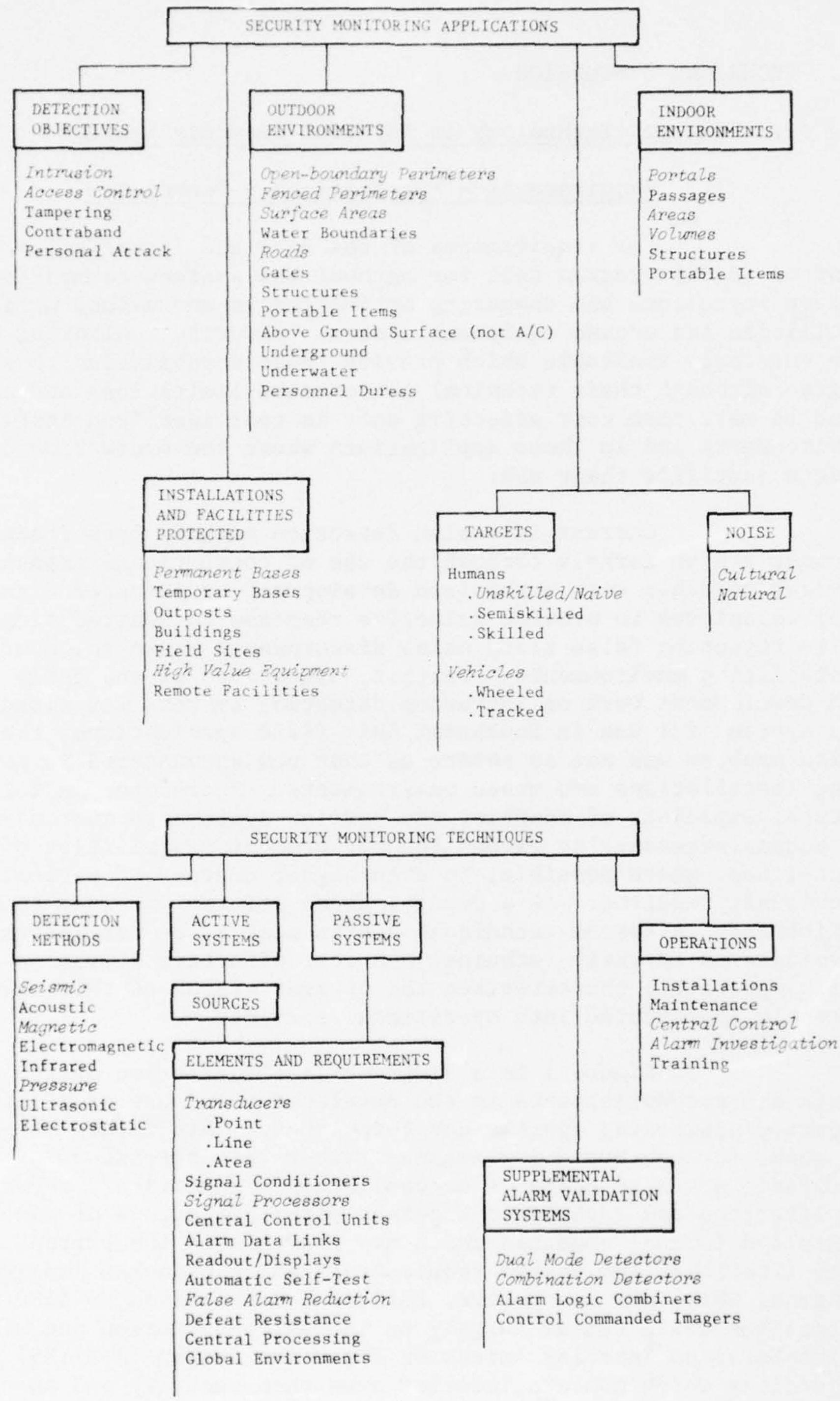
A. Current Technology in Physical Security Systems

1. Requirements - Applications - Techniques

The requirements of the Base and Installation Security Systems (BISS) Program call for methods and systems to monitor and detect intrusions and tampering activities in and around military facilities and around equipment assets. Security monitoring systems are currently available which provide these capabilities to a useful degree although their technical performance limitations and complexities tend to make them cost effective only in near idealized installation environments and in those applications where the protection of high value assets justifies their use.

Current intrusion detection methods have reached their present status largely through the use of conventional transducer devices together with emphasized development of advanced signal processing techniques to provide selective response to desired target signals while rejecting false alarm noise disturbances known to occur in the installation environments. Further, since much of the early research and development work on intrusion detection systems was aimed at providing systems for use in Southeast Asia field applications, the cultural noise problem was not as severe as that now encountered in permanent base installations and urban environments. Therefore, in following the natural expedient of adapting the earlier systems to current needs, it became necessary to extend the performance capabilities of these techniques, where possible, to even higher degrees of perfection than previously required. As a result, these efforts provided commendable refinements in system techniques and in most cases carried the equipment developments to their technical and cost effective limits -- a condition which accurately characterizes the present status of those systems most recently implemented into operational service.

Figure 1 is a diagramatic illustration of the general goals and accomplishments in the development and use of military security monitoring systems and techniques. This figure attempts to show, through broad impressions rather than precise details, the desirable ultimate scope of accomplishments in military security system applications and techniques together with indications of the achievements and topical emphasis which now prevails in the current technology (italics). The system requirements and approaches implied in this diagram, while not exhaustive, reflect a combination of BISS program objectives which center largely on intrusion detection and also the Joint-Services Interior Intrusion Detection System (J-SIIDS) program objectives which concern interior arms room security and associated applications.



Note: Italics show emphasis and/or achievements attained with current systems and technology.

FIGURE 1. GOALS AND ACCOMPLISHMENTS IN PHYSICAL SECURITY SYSTEMS

To those familiar with the general evolution and development of military intrusion detection techniques, two observations are immediately evident from the diagram, vis: (1) the major emphasis in current security system technology still focuses upon many of the same problems and requirements encountered in first developing the technical approaches for earlier less demanding applications; and (2) much remains to be accomplished, probably beyond the capabilities of most of the current techniques, in order to reach the ultimate application goals and the desired standards of operational success.

2. Transducers

Intrusion detection transducers, in the realm of current technology, consist of both conventional detector devices and specialized refinements of detectors operating on the same basic principles as the conventional detectors but offering certain advantages in sensitivity, noise reduction, and/or ease of installation over the conventional devices. These transducer configurations can be classified as being either active or passive in their operation and as offering either point, line, area, or volume surveillance. Moreover, it is noted that most of the transducers can be used either as point or line sensors depending upon their size and shape or whether they are configured singly or in closely spaced linear arrays. Also, some of the transducers respond to more than one form of excitation stimulus, which may be either an advantage or a disadvantage depending upon the target detection application and the installation noise environment.

Table I presents a general summary of intrusion detection transducers used in past security system applications and comprising the principal items of current operational transducer technology. Other transducer mechanisms and device concepts more recently considered for use but not developed to operational status and those that offer good promise for successful future development as advanced intrusion detection devices will be listed and discussed later. For outdoor intrusion detection applications, possibly the most effective transducer techniques developed so far are the Magnetic Intrusion Line Sensor (MILES) transducer and the Strain Sensitive Cable (SSC) electret line as listed in Table I. Both of these techniques function well as buried line sensors and the SSC has also been applied as a tamper activity and building entry detector. It is clear from the descriptions of these two transducers that they represent advancements and refinements over similar and more conventional transducer types used in earlier systems and can be regarded as specialized devices for security systems. These device achievements typify the merits of advanced transducer technology developments to which the program has been directed.

TABLE I. SUMMARY OF CURRENT INTRUSION DETECTION TRANSDUCER TECHNOLOGY

DETECTION METHOD	TRANSDUCER TYPE	TRANSDUCER DESCRIPTION	PRINCIPAL APPLICATIONS
SEISMIC	Electromagnetic	Inertial motion detector; velocity geophones rugged; low cost.	Buried point sensor; multi-element line array; detects human footsteps and moving vehicles.
	Piezoelectric	Inertial motion detector; accelerometer; rugged; high frequency response.	Structure-mounted point vibration sensor; detects tampering activity.
ACOUSTIC	Piezoelectric	Airborne sound pressure detector; flexural mode piezoceramic element on diaphragm or coupled directly into air medium; audio frequency range and ultrasonic frequency range.	Audio outdoor listening device (vehicle targets); ultrasonic indoor listening device (tempering activity); point or area sensor.
	Magnetic Induction	Passive loop magnetic field perturbation detector; balanced to far-field natural magnetic disturbances and electromagnetic noise by wire transpositions or differential loop connections.	Buried line sensor; detects ferromagnetic weapons and objects carried by intruders; also detects vehicles and water traffic;
	Magnetic Induction	Passive solenoid magnetic field perturbation detector; portable.	Point magnetic sensor or hand-held wand; detects ferromagnetic weapons and objects moving in close proximity.
MAGNETIC	Magnetic Induction (MILES Cable)	Passive, magnetic-cored gradiometer cable; balanced to far-field disturbances and electromagnetic noise; flexible magnetic core material also provides pressure-sensitive response to compressive stresses in soil; fast, simple installation capability.	Buried single cable magnetic line sensor with associated soil pressure response to walking intruders and ferromagnetic weapons carried by intruders.
	Magnetic Induction	Active balanced field induction detector; responsive to ferrous and nonferrous metals; adaptable to many portal configurations.	Portal surveillance; detects metallic objects moved or carried through doors, windows, passages; can discriminate ferrous vs. nonferrous objects.
	Microwave	Active microwave beam-interrupt line sensor; fixed or portable installation; separate source and receiver.	Microwave fence; detects intruding personnel or vehicles crossing beam-interrupt line.
ELECTRO-MAGNETIC	VHF Radar	Active ground-penetrating radar; penetrates typical soils 2 to 3 meters; resolves tunnels and voids of 1/2 to 1 meter diameter or larger; manportable.	Search system for detecting shallow man-made underground tunnels.

TABLE I. SUMMARY OF CURRENT INTRUSION DETECTION TRANSDUCER TECHNOLOGY - Continued

DETECTION METHOD	TRANSDUCER TYPE	TRANSDUCER DESCRIPTION	PRINCIPAL APPLICATIONS
INFRARED	Near IR	Passive photodiode and phototransistor infrared quantum detectors; small, low power; high sensitivity; noncryogenic.	Infrared line sensor; provides bounded field of view in which transient thermal anomalies or silhouttes are detected; detects personnel and vehicles.
	Near IR	Active infrared beam-interrupt line sensor; narrow beam.	Infrared fence; detects intruding personnel or vehicles crossing beam-interrupt line.
PRESSURE	Compressive Stress in Soil	Balanced fluid-filled hose; balanced Pressure Sensor (BPS)	Buried line sensor; detects walking intruders and vehicles.
	Compressive Stress in Soil	Balanced air-filled hose; Balanced Pressure Detection Component (BPDC); less soil dependent than BPS.	Buried line sensor; detects walking intruders and vehicles.
	Compressive Stress (SSC)	Strain sensitive cable (SSC); electric line; also provides response to seismic and structural vibrations through an enhanced triboelectric effect.	Buried line sensor; detects and classifies vehicles by wheel base dimensions; fence tamper detector.
	Compressive Stress	Charged wire-in-tube configuration; small teflon insulated wire loosely fitted and electrified in a copper tube; provides seismic and vibrational response; provides audio acoustic response	Buried line sensor; detects walking intruders and vehicles other; possible applications.
ULTRASONIC	Piezoelectric	Active beam-interrupt line sensor; above audible frequency range; narrow beam; subject to outdoor meteorological phenomena; portable.	Ultrasonic fence; detects personnel and vehicles crossing beam-interrupt line.
	Piezoelectric	Active standing wave or dipole detector; responds to changes in standing wave conditions in indoor rooms.	Area and volume intrusion detector; detects entry into unoccupied rooms.
	Piezoelectric	Passive ultrasonic listening device; responds to air jet noise, cutting torches, structural vibrations.	Indoor listening device; detects tampering noise; point or area sensor.
	Electret Line	Active ultrasonic; detects doppler shift with incursion of target.	Indoor or outdoor line type device; line in tape form which will adhere to non-porous surfaces.
ELECTROSTATIC	Capacitance	Charged wire or grid electrode; responds to proximity of transient material volumes whose dielectric constant differs from the static surroundings	Portal surveillance; detects the human body as it moves into close proximity of windows, doors, passages.

B. Signal Sources

In considering sensors for detecting intruders, it is useful to examine the nature of the intruder characteristics which might be exploited in a transducer mechanism. Since the targets of interest for this study are limited to humans and vehicular traffic, the data reported will be limited to these areas. Much of the intruder signature data reported here was derived from RADC-TR-72-126 (Solid-State Sensor)(1). This information is useful in assessing the feasibility of transduction techniques.

1. Human Targets

a. Acoustic Signatures

Sound pressure levels which are produced by walking men range from a low of 42.3 dB (relative to 0.002μbar) for 1 man walking at a range of 20 meters to a high of 50.7 dB for 8 men at a range of 2.5 meters. Ambient conditions will alter these values, however, these values give the general range of what might be expected.

b. Magnetic Signatures

A human intruder can only be detected by magnetic methods if he is carrying a ferromagnetic object such as a rifle. For this reason, detection ranges for magnetic sensors have usually been quoted for "one man with rifle" and studies have been done to determine the signature produced by this weapon. From data taken on ten M1 rifles (Cal. = .30) at a range of 2 meters, induced field magnetism ranged from a low of 3γ to a high of 14 γ ($1\gamma = 10^{-5}$ gauss $= 10^{-9}$ Telsa). The induced values reported here are dependent upon, among other things, the orientation of the object in the earth's field. Permanent magnetism (or remanent magnetism) is independent of the earth's field or the object's orientation. Under similar conditions, the permanent magnetism ranged from a low of 1γ to a high of 36γ . From this data it can be concluded that 1γ sensitivities are required for detection at 2 meters, but that a great many detections would be possible at this range with 5-10γ sensitivity.

c. Pressure and Seismic

As a man walks over the ground, he exerts forces on the surface which generates a time-varying pressure disturbance which propagates both downward and outward on the surface of the earth. The most difficult signal to detect is the stealthy intruder who walks very slowly. Most of the energy of such a source falls into the spectrum below 1 Hz.

Tests with a man walking normally (two steps per second) have shown that at a range of 30 meters, the level of the seismic particle velocity was approximately 0.6 μm/sec. This energy level was decreased by 4.5 dB at the rate of one step per second; rapid walking produced about 3 dB more seismic energy than normal walking. Two men walking produce signals which are about 3 dB above the one man level, 4 men walking produce seismic levels which are about 7 dB above the one man level. Surface wave frequencies ranged from 6 to 43 Hz with the largest spectral components in the 28-33 Hz range.

d. Infrared

The temperature of the human body is normally in the range of 36 to 37°C. At this temperature, the wavelength at which peak emission occurs is between 9 and 10 μm. The available radiant energy on the surface of a human will vary with emissivity which in turn is a function of skin texture and wearing apparel. The amount of available radiant energy normally falls in the 100 to 400 watts/cm^2 with 90% of the energy at wavelengths longer than 7μm.

2. Vehicular Targets

a. Acoustic Signatures of Vehicles

Dynamic tests made on various tracked and wheeled vehicles show wideband (20 Hz to 10 kHz) pressures that range from 77 dB (re. to 0.002 μbar) to more than 94 dB at a range of 50 meters. An octave band spectral analysis of the signals shows that the highest peaks lie in the 50 to 150 Hz range.

b. Magnetic Signatures

A considerable amount of data has been taken in classifying the magnetic signature of military vehicles. Because the magnetic anomaly is usually small in relation to the earth's field, results are observed as small deviations from the earth's field. For a large vehicle, 100γ disturbances may be observed at distances of 25-30 meters. For small vehicles, the 100γ range would extend out to only 6 meters and the 1γ range out to more than 25 meters. At a range of 15 meters, the smallest observed change for a variety of vehicles was 13γ .

c. Vehicular Seismics

Much data has been taken and published regarding the seismic signatures of vehicles. Particle velocities in the earth are dependent on range, site characteristics, vehicle type and vehicle

speed. Each one of these parameters can have a profound effect on the seismic signature of a vehicle.

A medium size tank at 8 meters will produce a particle velocity of more than 100 μm/sec. At 100 meters, this may vary from 2.9 to 41 μm/sec. An armored personnel carrier at a range of 100 meters will generate particle velocities in the range of 1.2 to 12.7 μm/sec.

The frequency content of the seismic signals can vary widely also but generally is in the range of 50 to 150 Hz. The frequency content is range dependent where higher frequencies tend to be filtered out at longer ranges.

d. Infrared

The peak wavelengths for maximum radiated energy from vehicles occur near the same wavelengths where maximum energy is radiated in humans (i.e., 9 to 10 μm). Therefore a single detector will satisfactorily function as a sensor for both types of targets.

For a single vehicle, the infrared signatures will vary according to the orientation of the vehicle. In the 9 to 14 μm band these levels will range from approximately 4o to 400 watts/steradian. At the shorter wavelength (i.e., the 3 to 5 μm band), the radiant energy will vary from 4 to 30 watts/steradian.

III. TRANSDUCING DEVICES

A. Acoustic Sensors

Acoustic waves may be distinguished from seismic waves by their lack of shear waves components. In this context, then, mechanical disturbances in fluids may be considered as acoustic signals. Several parameters may be utilized in detecting acoustic signals with the most common one being pressure. Transducers designed to sense acoustic disturbances in air fall in the category of microphones and it is this family that is discussed in the following sections.

1. Microphones

All microphones employ some type of diaphragm to provide an interface between the acoustic disturbance and the transduction mechanism. Some of the types of microphones in common use are the dynamic, piezoelectric and the electret or condenser microphone . A sampling of recent developments in these types will be discussed.

a. Electret or Condenser Microphone

The electret microphone can best be described as a condenser microphone with a solid dielectric. The primary difference between the two types is the fact that the electret microphone does not require a d.c. bias. Because their construction and characteristics are so similar in other respects, the two are grouped together for purposes of this discussion. In general, the sensitivity of the electret microphone corresponds to that of a condenser type with an external bias of 70 to 280 volts.

Although electret microphones first came into use during the Second World War, it wasn't until the 1960's that metalized thin films such as Mylar or Teflon were used in their construction. More recently the use of these polymers made possible a microphone having good mechanical qualities and a higher capacitance due to the thin spacing between the electrodes. While Mylar functions fairly well as an electret microphone, its characteristics are not satisfactory in a humid atmosphere. Teflon, on the other hand, was found to be excellent as far as its charge storage properties are concerned. The electret materials with the best electrical properties are the halocarbon materials Teflon FEP, Teflon TFE (flurofilm), and Aclor (CTFE).

Electret and condenser microphones have the good features of a flat frequency response, low distortion, low vibration sensitivity, good impulse response, insensitivity to magnetic fields,

and simplicity in design. An advantage of electret transducers is that they can be built in very small sizes and in a variety of shapes and sizes. The sensitivity is almost independent of size and shape.

One disadvantage of the electret microphone is the need for a high impedance preamp located near the detector element. This preamp is typically a single-stage low-noise field-effect-transistor (FET). The electrical noise of the electret-microphone system is limited then by the preamp input resistor and the FET. For a well-designed microphone-amplifier, the equivalent noise level should be less than 15 dB (SPL).

The electret microphone now accounts for about one-third of the entire production of Hi-Fi microphones. The success of the electret in these applications is primarily due to its acoustic quality and low cost. With respect to its acoustic quality, the electret microphone has been designed with low cutoff frequencies of 10^{-3} Hz. A microphone with this low frequency response can be constructed that is flat over a range of seven decades.

Carlson and Killen[2] describe a new design for a subminiature electret-condenser microphone which uses a nontensioned diaphragm. This construction permits the frequency response and the temperature coefficient to be independently optimized. The resulting microphones are characterized by low vibration sensitivity, noise level, and temperature coefficient, combined with a high degree of reliability.

Separating the "electret" function from the diaphragm makes it possible to select the electret material solely on the basis of its piezoelectric and charge retention properties and the diaphragm material solely on the basis of its mechanical properties. The frequency response of the microphone is related to the diaphragm mass and compliance. The diaphragm compliance is in turn related to the microphone sensitivity that can be obtained. Thus the lower the diaphragm mass, the higher the frequency response and sensitivity that can be obtained.

With respect to vibration sensitivity, the design reported here results in a microphone which is 25-30 dB less sensitive than a magnetic type microphone. The improvement over the typical electret microphone is about 12 dB and better than 25 dB when compared to a ceramic element. This design noticeably eases the requirements of vibration isolation where this is a problem.

In most electret microphones, a tensioned film or foil is fastened to a support structure. The diaphragm operates as a simple membrane with the microphone sensitivity related to the diaphragm tension. Since the tension is related to the temperature, the microphone sensitivity will also be a function of temperature.

Some films also change dimension as they absorb moisture and as such have a change in sensitivity related to the humidity. The design reported in this paper bypasses the problem of maintaining constant diaphragm tension by simply not tensioning the diaphragm in the first place. Tests on microphones using this type of construction show only a few tenths of decibels sensitivity over the range of -17°C to +63°C.

Carlson and Killen do not present absolute pressure sensitivity or noise figures for the microphones; however, the quality should be comparable to any good state-of-the-art electret microphone.

A paper by Nelson(3) gives the design detail for an electret microphone and companion preamp. This microphone-preamp combination is designed to be compatible with a telephone handset but is mentioned here because of the design which uses a single pair of leads for power and signals (phantom powering). The preamp presented is flat ($\pm$1 dB) from 100 Hz through 10 kHz. At 1 kHz, a maximum output level of +3 dBV across a 600 ohm load was obtained with a current drain of 30 mA. The dynamic range of the system is reported to be 84 dB.

Watson(4) describes the design of an electret type microphone with a package size resembling a conventional tie tac. A pin-like coaxial probe on the rear of the microphone interfaces with a small electronics assembly. This design permits the transducer to be placed in a good location without the microphone and its cable being visually obvious.

The design of the tie-tac microphone was directed toward commercial sales. Nevertheless, the goals defined in the development of the device have parallels with the objectives of a transducer for intrusion detection. For this reason, the design goals for the microphone are listed.

- The microphone had to be small and inconspicuous.
- The acoustical performance had to be satisfactory.
- Overall ruggedness and reliability of the design must be high.
- The cost should be low enough to permit competitive pricing.

The diaphragm assembly of the transducer consisted of a brass ring to which 25 μm film of a fluorocarbon plastic had been thermally bonded and coated with a conductive elastometric compound that resists corrosion in the presence of water and atmospheric pollutants. The electret was sensitized to yield a midband sensitivity of -40 dB (re $1V/N/m^2$).

An electronics module which is a part of the microphone houses a FET-resistor combination used to convert the high

impedance of the electret (>100 Megohms) to an output impedance of less than 200 ohms. Two basic circuit configurations are presented in the article. One circuit is a conventional FET source follower which is compatible with phantom powering. The second circuit is adaptable for self contained 1.35 volt battery operation and can be coaxially terminated. The nominal current drain is 150 μA. A small mercury battery is sufficient to supply the unit for more than a thousand hours of operation.

A paper by Rasmussen(5) describes efforts to advance the state-of-the-art in condenser microphone design for outdoor use. The objectives of the work were to provide protection against humidity and corrosive elements in the atmosphere, rain protection, improved wind-screening and protection against birds resting on the microphone. Some of the techniques described here could be applied to other micriophone types as well.

To protect against humidity in the microphone, other condenser types have used heating elements to keep the interior dry. The author describes a more positive approach by using an in-line dehumidifier. When used in 100% humidity, the dehumidifier requires drying out about once a month . Under normal conditions, the dehumidifier can be used for 6 months.

To combat corrosion, the diaphragm and backplate are covered by a thin protective film of quartz. The protective film is 0.7 μm thick and as such, only increases the mass of the diaphragm by 4%.

In this paper a rain cover is illustrated which permits permanent outdoor installation. Also, a windscreen is shown with spikes protruding from its top to prevent birds from roosting on it. Curves are shown giving the induced noise levels as a function of wind speed and frequency, at 0° and 90° incidence for the microphone with windscreen and rain cover.

b. Piezoelectric

In the past, piezoelectric (crystal) microphones have had the reputation of being low quality and cheap units. Modern piezoelectric microphones are neither cheap nor of low quality. In this type of microphone, a diaphragm is fastened directly to a stress-sensitive piezoelectric element which responds to acoustic pressure variations.

The usual piezoelectric materials are ceramics such as $BaTiO_3$ or crystals such as quartz or Rochelle salt. Recently polyvinylidene fluoride film (PVF_2) has been used in electroacoustic transducers as the piezoelectric element. The piezoelectric strain constant for PVF_2 is almost ten times larger than that of quartz. PVF_2 is also referred to as a thermoelectret since it is sensitized

by applying a high electric field at elevated temperatures. Thus it could be placed in the category of electrets but for this discussion will be compared to the other piezoelectric transducers.

PVF_2 films show the largest piezoelectric effect (g-constant) known in polymers. Other characteristics which PVF_2 has and are not shared by other materials are: (1) elements with a large surface area and extremely thin cross section can be produced; and (2) the film is highly flexible and light weight. A stereo headphone and high fidelity speakers using the PVF_2 element as the electroacoustic element have already been commercialized.

Table II provides a comparison between PVF_2 and other piezoelectric materials. The elastic stiffness of the PVF_2 material is more than one order magnitude smaller than those of the usual piezoelectric materials.

TABLE II. COMPARISON OF PIEZOELECTRIC MATERIALS

	Piezoelectric Constants		Elastic Stiffness	Relative Dielectric Constant
	d coul/N (10^{-12})	g V-m/N (10^{-3})	c dyn/cm^2 (10^9)	
Quartz	2	50	77.2	4.5
Rochelle salt	275	90	17.7	350
PZT ceramics	110	10	83.3	1200
$BaTiO_3$	78	5.2	110	1700
PVF_2	20	174	3.0	13

A paper by Tamura[6] describes various transducers including microphones and phonograph cartridges which have been developed using the PVF_2 films as the electroacoustic element. In this paper, a microphone is described which can be built simply by using only a thin film of PVF_2 and a polyurethane foam backing. The dimensional tolerances of each of the parts may be looser than in the case of the condenser or electret microphone. The sensitivity of the microphone is -74 dB (re. 1 volt/μbar) with a capacitance of about 700 pf. This capacitance value is approximately two orders of magnitude greater than that of conventional condenser microphones which means that the signal-to-noise ratio of the PVF_2 microphone is improved. Another feature of the element is that is it hardly affected by moisture and dust.

U.S. Patent No. 3,832,580 (27 Aug. 1974) which was granted to Yamamuro and Tamura[7] describes various transducers, including the microphone alluded to above which may be fabricated

from PVF_2 film. This patent which includes 8 claims and 26 drawing figures describes the construction of speakers, microphones, pickup cartridge for audio frequencies, and supersonic transducers for transmitting and receiving sonar.

Another U.S. Patent, No. 3,912,830 (14 Oct. 1975)[8] which relates to the use of PVF_2 for transducers, describes a method of producing a piezoelectric or pyroelectric element from PVF_2. In this method, an undercoating of a thermoplastic or thermosetting resin having negligible piezoelectricity or pyroelectricity is applied on the surface of the film, and metal electrodes are vacuum deposited on the surface of the undercoating.

The inventors claim this coating is necessary since the adhesivity between PVF_2 film and a metal layer is generally poor. As such, electrodes formed on the polymer film readily come off when rubbed by a finger and cannot endure vibrations for a long period of time.

The authors state that for overcoming this fault, the surface treatment of the polymer film by corona discharging or by organic or inorganic compounds has been proposed but tests have shown that such surface treatments do not in general improve the adhesivity of the film and in some cases, the durability is reduced.

The inventors discovered that a piezoelectric element having excellent durability can be produced by coating the surface of the film with a high molecular weight compound having good adhesivity to the film, and then vacuum-depositing or plating conductive electrodes on the material. Practical examples of high molecular weight compounds are epoxy resin, an acrylic resin, a chloroprene resin, or dichlorobutadiene resin, a phenol resin and a vinyl acetate resin.

In a test of the method, the authors cite a stripping test where adhesive tape was applied to the vacuum coated aluminum. When the tape was peeled off, no stripping of the aluminum electrode was observed. On the other hand, when aluminum was vacuum-deposited on the surface of the PVF_2 film directly, the electrode was readily stripped off by the adhesive tape. Tests also showed that the coated films suffered no loss of piezoelectric sensitivity from the treatment.

c. Semiconductor Microphones

U.S. Patent No. 3,639,679[9] describes a microphone which includes a permanent magnet having an air gap in which a semiconductor diode sensitive to a varying external magnetic field is suspended. The diode is connected to a diaphragm which when vibrated by acoustically generated signals, will cause the diode

to oscillate in the air gap of the magnet. This movement of the diode related to the magnet modulates the current through the diode thus generating an electrical signal. The inventor implies that the advantage of this microphone over crystal, electrical-, and ferro-electrical microphones is its lower impedance. No sensitivity figures are given.

Another microphone using a semiconductor as a strain sensitive element is described in a paper by Rikow and Miura[10]. The element which is a cantilevered piece of bulk silicon, makes it possible to make acoustic measurements in rain or dust. The sensitivity of this microphone is -85 dB (re. 1V/μbar) with a noise level of less than -126 dBV when a biasing current of 10 mA is applied. The response of the microphone does not vary more than several dB between .100 and 10 kHz.

Environmental testing of the microphone showed little degradation of performance with temperature, humidity and soaking in water. A 3-month test of exposure to sand, dust and smog showed very little change in sensitivity.

The paper also presents a possible scanning system for digitizing the microphone output and transmitting the waveform through a modem and then to a telephone line.

B. Magnetic

Major areas of magnetometer development which are both technologically significant and have had recent research efforts applied to improve their performance include fluxgate, thin film, resonance, and superconducting magnetometers. More recent developments are based on solid-state phenomena such as Hall effect, magnetoresistance, and magnetooptic devices.

1. Magnetoresistance Magnetometry

Pure bismuth has a magnetoresistance which increases by a factor of 1.5 in a field of 12 kG. Other materials such as InSb or InAs have a higher sensitivity. Since resistance measurements are so easy to make, it would appear that the magnetoresistance element would be an ideal sensor for magnetic fields. The general characteristic of the bulk magnetoresistance effect, however, prevents its widespread use. The device is nonlinear and exhibits a temperature dependence that restricts its use to applications where temperature control is possible and the magnetic field conditions are within a narrow range.

2. Inductance - Variation Magnetometer

A different type of thin film magnetometer uses a coil coupled to the "hard-axis" of a thin film, or a group of films, and exhibits an inductance which is dependent upon the "easy-axis" static field.

A thin-film inductance-variation magnetometer described by Bader[11] describes a simple and effective magnetometer which can be constructed using two transducers with opposing film magnetization sensors, in a self-excited balanced configuration. The circuit requires very low operating power and, with the addition of magnetic feedback, is capable of resolving field changes on the order of 0.1γ. The resolution is limited by film-generated noise and can be used for the detection of smaller field changes by increasing the planar areas of the films.

To utilize the induction-variation phenomenon, the circuitry for the transducer must sense inductance changes. To do so, a compromise between operating frequency and coil turns must be realized. This paper illustrates and describes a transducer which consists of 22 turns of wire around·6 film substrates of low magnetostruction Ni-Fe which are 19 mm square and 0.2 mm thick.

The dual transducers described here are utilized in a self-excited Colpitts oscillator where the frequency is determined by the sum of the transducer inductance. The r-f voltages developed across the transducers are individually rectified and summed with opposing d-c polarity, resulting in an output which is zero at zero applied field and which goes positive or negative according to the polarity and magnitude of the applied field. The response is linear for small fields. It is also noted that oscillator frequency is not involved in the output voltage vs. field relationship; thus, frequency drift due to thermal effects are of no importance.

For the circuit described, oscillator noise is cancelled out when the inductances are balanced. For an unbalanced condition such as that produced by an applied field, the noise cancellation becomes imperfect and the noise level increases. A solution to this unbalance noise is through the use of magnetic feedback to maintain a nearly zero applied field environment. When used with a high performance operational amplifier, an equivalent input noise of less than 1 microvolt in a 10 Hz passband is achieved and is capable of resolving 0.1γ with a sensitivity of 1 volt/gauss.

In summary, the thin-film inductance variation magnetometer is inherently suited to applications requiring simple circuitry and low power drain. Its principal limitation as stated by the authors, is one of obtaining the perfect balance needed for absolute measurements in the 1γ range. For intrusion applications, this should not be a problem, however, since in general the perturbation about some background level is all that is required. The techniques described in the paper are suited for detecting field changes over the 0.01 Hz to 10 kHz passband and at magnetic amplitudes ranging from 0.1γ to $2 \times 10^5\ \gamma$. With a sensitivity of 0.1 gamma, it should be possible to detect a side arm at a distance of 4 meters.

3. Flux Gate Magnetometer

Another relatively inexpensive magnetometer is the flux gate type. This device which uses an inexpensive molybdenum permalloy sensor can also detect field changes of the order of 0.1γ. As suggested by Kovattana, et. al.[12], a relatively inexpensive barrier of flux gate sensors could be built if a single set of electronics were used if the sensors in the chain were sequentially scanned using multiplexing techniques. Two papers are discussed here which outline recent advances in fluxgate magnetometry.

Gordon and Brown[13] discuss recent advances in fluxgate magnetometry and the application of high quality sensors for absolute measurements of weak fields, and the development of compact inexpensive low-power devices for various search and surveillance operations.

A fluxgate magnetometer is a device for measuring magnetic fields by utilizing the nonlinear magnetic characteristics of ferromagnetic core material in its sensing element. The emphasis in these instruments is the measurement of small variations in magnetic fields (1γ) in the presence of a large field of approximately 50,000γ.

Gordon mentions the variety of fluxgate magnetometers that have flown in more than 40 satellites. Most of these were used in earth orbits and had detection range of $\pm$ 10 to $\pm$ 100γ with frequency responses in the 0 to 10 Hz range. Sensitivities listed range from $\pm$ 0.0625γ to $\pm$ 80γ with most listed at 0.25γ. Magnetometers for satellite applications must have a wide dynamic range, low power, small volume, and wide temperature variations and as such, share some of the design goals needed in intrusion detection instrumentation. At the time this paper was written several small battery-operated fluxgate instruments were being marketed commercially. These instruments have, however, only one to a few gammas resolution, battery life of 100 hours and weights from 2 to 5 pounds. In the area of search and surveillance applications, the detectors used sacrifice accuracy and stability in favor of simplicity and small size. Current experimental and theoretical effort is aimed at further improvement of the residual noise and offset for absolute instruments and at minimizing power, size, and cost of the small portable devices.

Another paper by Acuna[14] describes in more detail the magnetometers developed for the Pioneer 11 and Mariner-Jupiter-Saturn missions. The instruments described cover the range from 0.01γ to 2 x 10^6γ with optimum performance characteristics and low power consumption.

The fluxgate magnetometer for the Mariner-Jupiter-Saturn mission (MJS'77) consists of an array of 4 triaxial fluxgate magnetometers. Two instruments cover the range from 0.015γ to 5 x 10^4γ in 8 dynamic ranges. The remaining two units are used for the high field ranges.

The instrumentation consists of a low noise AC preamplifier stage of conventional design. A CMOS quad-bilateral switch is used as a synchronous detector to recover the second harmonic signal and its output is applied to a high gain integrated circuit operational amplifier. The sensors for the low field units are constructed using low noise, high stability, 2.54 cm diameter ring cores developed by Gordon et al[15] at the Naval Ordnance Laboratory.

For many magnetometer designs, the sensor must be mounted in the immediate vicinity of, or within the sensor support electronics package. As such, they are subject to the magnetic fields produced by the component parts in the assembly. This restriction is not applicable to the MJS design and the sensors may be mounted at large distances from the sources of contamination.

In the circuitry described, stable sensitivities of 1-10 mV per γ from the low field sensors were achieved. This sensitivity should be compared to previous sensitivities of the order of 25 μV per γ. The rms noise level for the instruments as measured in a standard magnetic shield was 0.013γ for a 0 to 10 Hz bandwidth. Power consumption for the low field unit is 120 mW.

4. Magnetic Gradient Vehicle Detector

The design, analysis and selected measurements of a new type of vehicle detector called a magnetic vehicle detector (MGVD) is described by Mills[16]. The primary advantage of this type over more conventional types (inductive loop) is, according to the author, the ease of installation and improved performance. The MGVD consists of a 2.1 meter x 3.8 cm x 1.3 cm transducer, dual triaxial lead-in cables, and roadside detectors electronics. The transducer is installed in a 1.5 cm wide x 4.5 cm deep slot in the pavement surface, transverse to the direction of vehicle traffic. When a vehicle approaches the transducer, eddy currents are induced in the vehicles frame and the resulting magnetic field is sensed by the transducer. References to publications containing schematics and construction details are included in the paper.

The basic operating principle of the MGVD is as follows. A sinusoidal current (f = 100 kHz) is coupled to a transmitter coil. The magnetic field generated by the transmitter coil induces approximately equal voltages in two differentially connected colinear receiver coils (in phase opposition) such that the sum of the two coils in near zero. When a vehicle passes over the coils, this balance condition is upset and a net voltage much larger than zero is induced. For a large target, a maximum voltage of about 5 mV is available at the coils output. This low level signal is amplified by a tuned amplifier with a gain of 90 dB and then rectified and filtered. The

resulting dc signal is threshold detected to provide target discrimination.

Production prototype models of the MGVD have been evaluated with reference to noncooperative classification of vehicles passing over the transducer. In this phase of the study, amplitude and phase signatures of various types of vehicles were measured. The amplitude/phase signature for a Volkswagen is given in the paper and data comparing the test results to an induction loop type data are given.

In summary some of the advantages of the MGVD are as follows:

1) Reduced transducer installation time and costs.
2) Greater sensitivity.
3) Improved detection stability allows d.c. (infinite presence) mode of operation.
4) Detection sensitivity is independent of "lead in" cable length.
5) Improved accuracy in determining vehicle speed.
6) Possibility of uniquely identifying and classifying vehicles by processing vehicle amplitude and/or phase signatures.

C. Electromagnetic

1. RF Doppler Motion Detector

A successful motion detector may be constructed using an active microwave source and the Doppler shift generated by the movement of the target. In the past the use of microwaves for use in trusion sensors has been limited by the non-availability of effective solid-state sensors. Recently, however, advances in solid-state technology have made possible small portable radars which are reliable and cost effective for some intrusion applications.

The solid-state development making low cost, reliable radars possible in the Gunn effect or GaAs devices known as Gunn diodes. The Gunn effect is produced when a high electric field is produced across a piece of gallium aresenide with ohmic contacts. With this configuration a bulk negative resistance is produced which leads to the formation of a high field domain. This domain propagates through the device at approximately the electron's velocity and generates an oscillatory current through the device. If the diode is placed in a resonate cavity, microwave energy can be extracted from it. The practical frequency limits for the oscillator are 1 GHz (C-band) on the lower end and 40 GHz (Q-Band) on the other.

Microwaves sensors are used for both indoor and outdoor application. The indoor unit can cover areas up to 10,000 ft^2. The type of coverage delivered by a given unit can be changed by varying the antenna. A broad beam antenna operating in the x-band is approximately 3.5 inches (8.9 cm) in diameter. A larger antenna of approximately 8 or 9 inches (21 cm) will generate a narrow beam about 10 degrees wide and a range of 300 feet (91 meters) or more.

Microwaves are absorbed by building materials by varying attenuation rates and as such may penetrate into areas outside the protected area. This property makes them susceptible to false alarms which are not encountered using infrared or ultrasonic devices. When used in combination with other detectors or singularly in areas where containment is not a problem, the Doppler microwave detector can be an effective intrusion detector.

At the highest frequencies, the modes of oscillation in Gunn effect devices are transit-time limited and are subject to a general power frequency limitations in which the relative output power decreases as $1/f^2$ (17). The absolute level of output power is controlled by the conversion efficiency and the minimum impedance level attainable in the microwave circuit. At lower frequencies, the devices are thermal-dissipation limited and the output power is related to frequency by a 1/f law. Figure 2 shows an idealized plot of output versus frequency for continuous wave operation. The dashed curve in Figure 2 shows how actual data agrees with the simple theoretical laws. In practice the efficiency is about 3 to 12% for Gunn devices.

A paper by Pauker, et.al.[18] reports on a study carried out to investigate the mechanism of a Gunn diode proximity detector which was designed to be used as in inexpensive alarm device. The circuit used is simple and consists of a resonator with a Gunn diode, connected to a single antenna, used for both transmitting and receiving.

Unlike the other papers which are referenced in the sections which follow, Pauker does not explain the alarms mechanism on the Doppler phenomenon. He believes the effect is one of pulling by the load impedance that is seen by the diode. If the impedance varies, by the change in the position of a reflecting target, it gives use to power and frequency changes which modify the bias working point.

Another article based on information by M.L. Nyss[19] describes an intruder detector using a Gunn effect oscillator. This article gives a good background on the Gunn effect and Gunn effect devices. The author also goes into some detail on the Doppler effect with reference to intruder applications. The carrier frequency for the device is bracketed between 18 GHz (above this frequency the

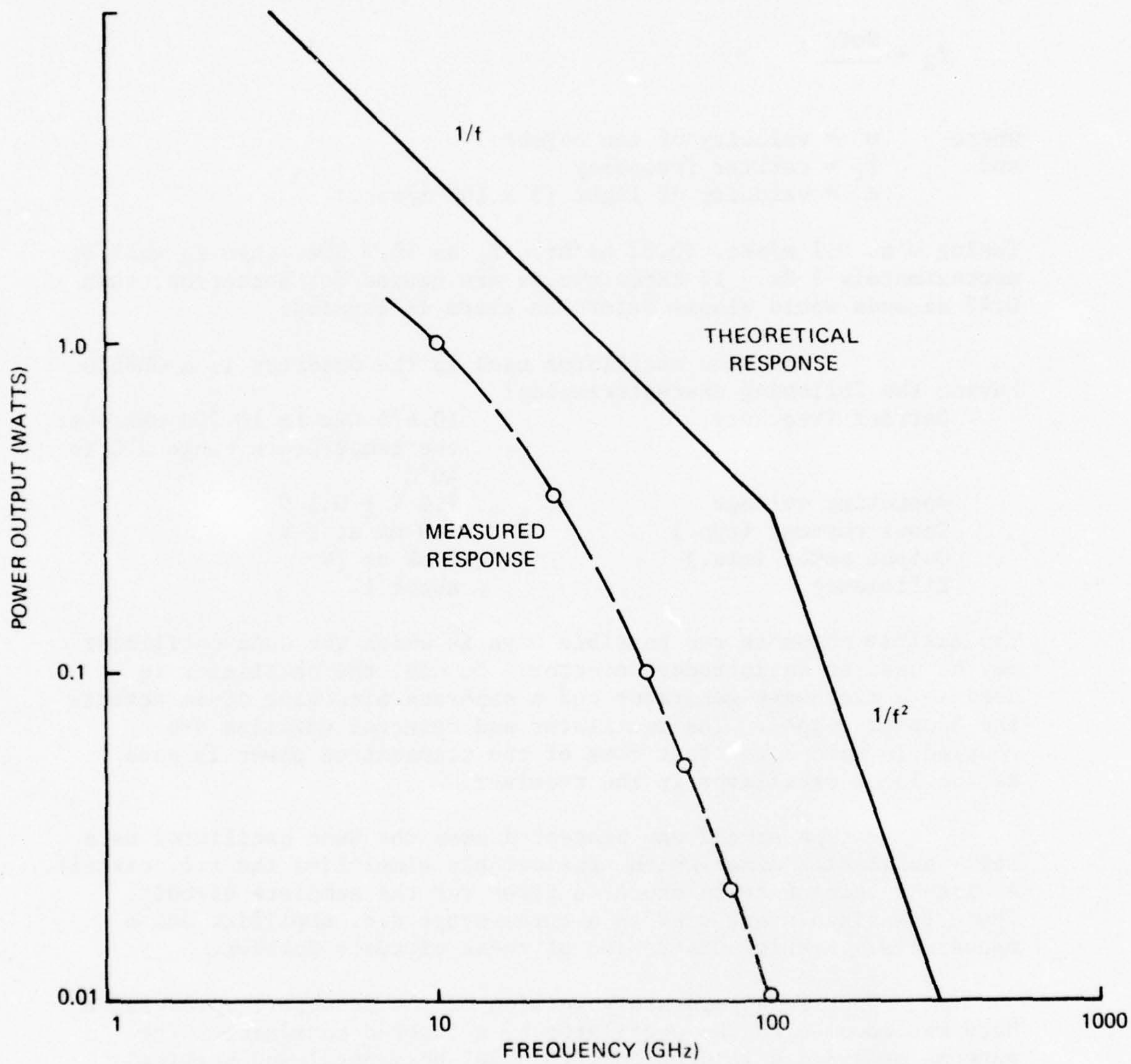


FIGURE 2. OUTPUT POWER VS. FREQUENCY FOR GUNN EFFECT DEVICES OPERATING IN THE CONTINUOUS WAVE MODE

detector circuit gets complicated and expensive) and 1 GHz (below this frequency the frequency shift would be too small for detection). The frequency selected for the device discussed here is 10.7 GHz. The frequency shift f_d is given by:

$$f_d = \frac{2\upsilon f_t}{c}$$

where υ = velocity of the object
and f_t = carrier frequency
c = velocity of light (3×10^8 m/sec.)

Taking υ as 0.1 m/sec. (0.22 mi/hr), f_t as 10.7 GHz, then f_d will be approximately 7 Hz. If three cycles are needed for detection, then 0.42 seconds would elapse before an alarm is sounded.

The Gunn oscillator used in the detector is a CL8630 having the following characteristics:

Carrier frequency	10.675 GHz to 10.700 GHz over the temperature range 0°C to 40°C
Operating voltage	7.0 V $\pm$ 0.1 V
Input current (typ.)	140 mA at 7 V
Output power (min.)	8 mW at 7V
Efficiency	about 1%

The **article** presents two possible ways in which the Gunn oscillator may be used as an intruder detector. In one, the oscillator is used as a microwave generator and a separate microwave diode detects the Doppler signal. The oscillator and detector cavities are coupled in such a way that some of the transmitted power is used as the local oscillator in the receiver.

A second way presented uses the Gunn oscillator as a self-oscillating mixer which considerably simplifies the r.f. circuit. A circuit using 6 transistors is given for the complete circuit. These transistors are used as a three-stage d.c. amplifier and a monostable. A brief discussion of these circuits follows.

In a laboratory version of the detector, a waveguide horn was coupled to the oscillator by a tapered waveguide. The antenna provided a 16 dB gain with a 30° horizontal and vertical beam-width. The oscillator stage requires approximately 140 ma at 7 volts (1 watt).

The three stage d.c. amplifier has a gain of 66 dB and goes into saturation for input signals exceeding 2.5 mV. Its response is from 20 to 300 Hz which covers the frequencies for intruders moving at a walking pace. The output signal from the

d.c. amplifier is used to trigger a 10 sec. monostable but could also be used to drive a reed relay or a number of output devices. By making the amplifier frequency selective, the unit could be tuned for objects moving only within a certain velocity range.

The range of the unit was tested by using a 30 cm x 30 cm aluminum plate mounted on a movable trolley. The tests showed that the detector works satisfactorily for small objects up to a range of 5.5m and could be effective up to at least 8 m for human intruders. The author states that the main obstacle to extending the range further is the noise of the oscillator.

A third paper concerning the use of Gunn effect devices is authored by Myers[17]. He also gives a good discussion of Gunn effect devices including avalanche diodes (IMPATT) and TRAPATT devices. A good comparison of power output vs. operating frequency (1 to 100 GHz) is presented and compares the Gunn diode to other solid-state microwave systems.

In addition to attributes of the Gunn diode already discussed, he mentions that the devices are long-lived, stable with regard to environmental changes such as temperature, and low cost. The waveguide cavity configuration provides the lowest noise output and gives the best stability because of its high Q-factor. A typical waveguide cavity could be expected to have a loaded Q-factor of around 500 whereas the corresponding figure for a microstrip circuit would be around 20.

The most sensitive detection method using Gunn diodes is to use a separate detector diode mounted in a separate cavity. After detection, an amplifier of 80 dB gain is used to drive other signal processing circuits. A block diagram of such a system is presented in the paper and a commercially available model is shown which has a range from 10 to 100 m.

Gunn devices can also be used in the pulsed mode with power levels up to a few tens of watts being possible. By combining several devices, powers of up to 100 W peak are attainable. Small radars of this output capability which are being used for battlefield surveillance have ranges in the 2.5 km range. A complete radar system that can be made small enough to be held and used in one hand has been developed by the Royal Radar Establishment but to date are not in as common use as the c.w. devices.

An article in CEE[20] reviews a commercially available Gunn diode motion detector which is manufactured by Philips Electron Devices. Designed for use as an intruder detector, the unit can be flush mounted in a wall or ceiling and can monitor a whole room.

The unit (CL8963) which operates in the X-band (10.525 GHz) contains a Gunn oscillator, mixer cavity, low-noise Schotky barrier diode detector and a low gain (5 dB antenna), requires the addition of a power supply and audio amplifier to amplify the Doppler audio output. A return signal which is 100 dB down when compared to the radiated source is received from a man target (1.0 m^2 radar cross-section) at a distance of 15 meters. If the background is free of moving objects or vibrations, a path loss of 125 dB may be tolerated to give a range of 25 meters. The range may also be increased by the use of a high gain antenna. Power requirements are 7 volts dc at about 140 mA (1 watt) to achieve a radiated power of about 8 mW.

The following table lists other commercially available microwave motion detectors. The specifications and prices were obtained from a 1976 catalog with pricing information based on quantities of 10.

Model No.	Freq. (GHz)	Antenna Pattern	Range (meters)	Power In	Size (cm^3)	Wt. (kg)	Price
R4-001	10.525	30°H.6V.	0-30	12VDC @ 0.8A	3.5 x 2.4 x 2.8	2.95	$306
D9-004	0.915	omni	6.1	12VDC @ 0.07A	1.8 x 1.4 x 1.2	--	$210
522-001	10.5	Adjustable	0-30	12VDC @ 0.15A	---	3.6	$216

Shorrock, et.al.[21] describe a perimeter detection system which uses a microwave curtain which is effective for a distance of 75 m (250 feet) between transmitter area receiver antennas. In this system the microwave transmitter and receiver antennas are identical and highly directional in the horizontal plane but less so in the vertical plane. The result is a curtain of microwave energy which is up to 1.8 m (6 ft.) high and up to 0.9 m (3 feet) thick. The level of the received signal is constantly monitored and when a human intruder walks through the active zone, this monitored level may either increase or decrease. The system operates in the X-band with a Gunn effect device used in the transmitter. The receiver microwave detector is a Schottky Barrier diode.

If this system is to be operationally viable, it is essential to keep the false alarm or nuisance rate low. Typical items which can cause false alarms include weather related phenomena, small animals (walking or flying), waving vegetation and wind-borne objects such as paper and leaves. The author states that the nuisance alarm rate is basically a function of system sensitivity and may be set according to operational requirements. Under normal recommended settings, the detection probability for a human intrusion is greater than 98% with a higher detection probability attainable at the expense of an increased nuisance alarm rate.

The microwave fence is specified to operate over the range of -10°C to +45°C. The power requirement is a nominal 24 volts AC or DC with a total current drain of 0.30 amperes. It is normal precedure to return both power lines and signal cables to a manned post where fence status is displayed.

Temporary protection can be offered by setting up portable microwave fences around protected areas such as parked aircraft. This may be accomplished by using 4 fences in a box fashion or 3 in a triangular fashion.

An obvious application of the microwave fence is in parallel with an existing wall or fence. By this means the unit can be used to detect attempts to scale a wall or climb a fence. When used in an internal environment, the overall sensitivity of the system can be enhanced to provide virtually impenetrable zones. When used in a corridor, the corridor itself acts as a funnel for the microwave energy and thus provides protection for the entire corridor. The transmitter and receiver units are 1 m long and 13 cm in diameter with both units weighing 3.9 kg.

D. Imaging Systems (Infrared and Visual)

The passive infrared receiver is suitable for use as an intrusion detection sensor in a wide variety of deployments, indoors or outdoors, and can be designed as an area detector, a volume detector, or a perimeter detector. The detectors so designed may be imaging or non-imaging. Those which are in the category of infrared imaging detectors are sometimes referred to as night vision systems or thermal imaging devices. The emphasis in infrared imaging devices during the past few years has resulted in rapid advances but many of the systems remain relatively complex and costly. Therefore, the developments in these areas which are of prime interest are improvements in detection capability without complexity or cost increases or detectors which reduce costs and/or complexity without sacrificing quality.

1. Charge Coupled Devices

The imaging detector which has received the bulk of the attention in the last couple of years is the charge coupled device (CCD) imager, and the charge-injection device (CID). Television type instruments using devices (for both visable and infrared wavelengths) are nearing a volume production phase. However, technology in these areas is still evolving at a rapid pace and efforts in the infrared bands are aimed at improving resolution in the field of view without increasing the cost and complexity of the IR optical system.

Like every other electronic image sensor, the CCD converts light quanta into charges that can be stored on a point-to-point basis and then read out in sequence. But unlike conventional television camera tubes, it does not need the complex, power consuming apparatus of a scanning electron beam.

In CCDs, the basic charge-coupling principle consists of storing carriers in potential wells under depletion-biased electrodes, and of moving these carriers from beneath one electrode to beneath the next by appropriate pulsing of the electrode potentials.

For imaging purposes, the field-of-view is focused onto the surface of the device. As the light quanta is absorbed, a hole-election pair is generated with the quantity of charge proportioned to the intensity of the image. In this manner, a spatial charge representation of the scene is stored in the device. As a clock signal is applied to the device, these charge packets are shifted serially from storage site to storage site until all charges reach the output stage.

Tompsett, et.al.(22) discuss the state-of-the-art in CCDs as of early 1973. At that time a 1,500-element four-phase line-scanning device had been fabricated. For imaging purposes the self scan in the linear array was horizontal and a mechanical vertical scan was used for the other dimensions.

In area arrays, the fabrication and testing of a 32-by-44 element array is discussed. The sensor consisted of an array of charge transfer lines to which the transfer pulses can be applied via switches operated by a line-address shift register.

A second type of device uses the "frame transfer" principle. In such an array, the light generated charges are all transferred to a lower section of the chip during a single clocking period while a new field is generated in the upper part. Then the information which is stored in the lower section is read out one line at a time and transferred to an output diode.

A frame-transfer device having 106 vertical registers, each 128 elements long (13,568 elements) is also reported in this article. The element size is 30 x 32 μm^2, and the active area of the chip was 3 x 5 mm^2. Figures in the article show an image reproduced using such a device operating at a 1 MHz clocking frequency. In the frame/field-transfer mode, the number of elements used to form the pictures is 64 x 106. By increasing the integration time and accepting additional smearing, the field 128-by-106 elements may be used as an image sensor.

Defects in the devices reported by Tompsett included short circuits in the detector elements which cause dark or white spots and lines in the displayed image. Another problem reported was blooming which is caused by the lateral spreading of charge from an intense spot of light.

A paper (30 pages) published in early 1975 by Barbe[23] presents more detail on the principles involved for imaging devices using the charge-coupled concept. A unified treatment of the basic electrostatic and dynamic design of CCD's based on approximate analytical analysis is presented. Clocking methods and tradeoffs are discussed. Driver power dissipation and on-chip power dissipation are analyzed. Properties of noise sources due to charge input and transfer are summarized. Low-noise methods of signal extraction are discussed in detail.

The state-of-the-art linear arrays at this time was 500 to 1728 resolution elements offered by four manufacturers. Resolution elements for area imaging chips were 256 x 220 (Bell Labs), 244 x 190 (Fairchild), 244 x 188 (GE), 512 x 320 (RCA) and 150 x 100 (TI). Tradeoffs in area-array performance from a systems point of view and performance predictions are presented in detail.

This article concludes with a section on infrared devices. There are basically three ways in which the charge-coupled concept can be used in infrared imaging. 1) A silicon CCD can be used to multiplex an array of infrared detectors, 2) a silicon CCD can be used to provide time delay and integration (TDI) for an array of IR detectors, and 3) a CCD or CID can possibly be fabricated in IR-sensitive semiconductors to provide monolithic infrared CCD's (IRCCD's).

The multiplexer implementation approach has two problems -- crosstalk between channels at the CCD output due to transfer inefficiency, and the low-noise injection of charge packets into the CCD which are proportioned in charge to the voltage at the outputs of the detectors. Reliable fabrication is a major concern in the TDI approach. The third approach, which is the monolithic IRCCD has the problems that 1) most technologies in suitable semiconductors are not well developed, 2) the high-background photon flux in the IR saturates storage cells quickly, and 3) the combination of high-background photon flux and low contrast imposes severe limits on the tolerable amount of nonuniformity of response (from cell to cell).

A considerable amount of development effort going into CCDs is to make a detector that can replace the commercial television quality, vidicon tube. A device that is close to this goal has been produced by RCA. The imaging detector (SID 4123), and its companion camera (TC 1155) uses a centroid system to achieve full TV resolution. The camera employing this device sells for $2600 to $3800.

Fairchild has available a 100 x 100 element camera (MV201) and a 244 x 190 element camera (MV221) which uses imager CCDs. The MV221 has enough resolution to be used for security systems where the quality of commercial TV is not needed.

General Electric is applying a considerable amount of effort in charge injection types (CID) of solid state imaging devices. Improved techniques have resulted in CIDs becoming comparable to the CCD in many ways, including scanning speed, array density and performance. GE's arrays can only be purchased as a complete camera or as an imager with appropriate signal devices. The TN2000 is available as a 1/4 scale TV compatible camera selling for $4000. A second camera is designed for instrumentation applications and is available with 100 x 100, 130 x 190, or 200 x 250 arrays.

Fairchild's entry into the "vidicon replacement type CCD" is an area array with 488 x 380 imaging sites. This device which is still in the development stages is due for production late in 1976.

Table III lists manufacturers of solid-state imaging devices along with their mailing addresses. Source of information is reference (24).

TABLE III
MANUFACTURERS OF SOLID STATE IMAGING DEVICES

MANUFACTURER & ADDRESS	DESCRIPTION
Dumont/Thomson-CSF 750 Bloomfield Avenue Clifton, New Jersey 07015	Currently developing 1 x 256 and 1 x 512 CCD line imagers.
Fairchild Camera and Instrument Corp. Charge Coupled Devices 4001 Miranda Ave. Palo Alto, Ca. 94304	Produces a complete line of both linear and area charge coupled device (CCD) imagers. Linear units range from 1 x 256 to 1 x 1728 elements, and area imagers range up to a 244 x 190 element array, and are intended for TV type applications. A 488 x 380 element, TV-compatible imager is in development.
General Electric Company Tube Products Dept. Imaging and Display Products Electronics Park Syracuse, New York 13201	Full line of CID (Charge injection device) imagers available, including CID camera.

Table III (cont.)

MANUFACTURER & ADDRESS	DESCRIPTION
Hughes Aircraft Co/IPD 6855 El Camino Real Carlsbad, Ca. 92008	Current imaging product development activity combines extrinsic silicon photoconductors and CCD's on a single substrate to produce a 1024 element infrared imager.
RCA Corp. Solid State Div. Electro-Optics and Devices Lancaster, Pa. 17604	CCD imagers.
Reticon Corp. 910 Benicia Avenue Sunnyvale Ca. 94086	Linear and area self-scanned photodiode arrays range from 1 x 16 to 1 x 1872 elements; area arrays are either 32 x 32 or 50 x 50 elements. Larger linear units have sensors aligned on 1 mil centers for high resolution. Scan rates are continuously variable to 10 MHz. A full line of scan cameras and controllers using these arrays is also available.

2. Image Intensifier Technology

A recent entry into the image intensifier field is the GEN II. This intensifier provides a significant reduction in the size and weight over the three-stage image intensifier tube (called GEN I). It also has nonblooming advantages over its predecessor. Even with the improvements noted above, the GEN II image intensifiers still utilize only about 0.1% of the available night sky glow. This is because the tube is effective only to 0.9 µm. Thus effort has been expended on the GEN III type of device which will give an increased range performance of up to 3 times the GEN II.

A paper by Needham[25] describes the new generation of image-intensifier tubes. The tubes discussed have intensification factors as high as 100,000 in spaces as small as 65 cm^3, including power supply. Their production cost is projected at about $750. This lower cost as compared to other tubes opens up the possibility of using it as a preamplifier for a conventional television camera tube, making feasible the use of low-light-level surveillance in security systems where cost is important.

The applications of image intensifier tubes fall into 3 categories: direct viewing, low-light-level television, and gated viewing. For direct viewing, the tube is designed into binocular type instrument. These may be helmet mounted and are designed with a wide field of view (approximately 50°).

A number of starlight telescopes weighing only 1 or 2 pounds have been manufactured using image intensifier tubes. The telescopes typically have a choice of screw on objective lenses which may be selected for the desired field of view. Thus, the devices may be used as pocket viewers for general security work.

Using the tube as a preamp for a conventional camera has already been mentioned. In surveillance systems using this type of sensor, the sensitivity of the vidicon is increased far beyond typical illumination requirements.

In the gated application of the tubes, the intensifier can be gated on for periods of less than 1 μsec. This approach allows the user to see through barriers of fog, mist or smoke screens. The principle of operation is as follows. A laser is pulsed to illuminate the target at a given range. If the intensifier output is gated on at the proper time, only light which has been reflected from a particular range will be detected. Since light reflected from intermediate ranges is not detected, the system is capable of penetrating partially opaque barriers with relative target-to-barrier gains in excess of 140 dB.

R.A. Spande[26] describes photographic equipment equipped with image intensifiers. In security work, the need sometimes arises for positive identification capabilities from photographic imagery. Even with the fastest films available, conventional photographic equipment cannot meet this requirement in darkness. Spande describes and shows illustrated examples of mating the intensifier tubes to photographic cameras.

On nights where the sky is overcast, moonless and in poor visibility weather, even the best image intensifier tube may be limited by the lack of light. To overcome this difficulty. Cleverly[27] describes an artificial covert illuminator which may be added to any night viewing system. The illuminator which has an average optical power output of 7, 12, 17, or 18 watts at a wavelength of 0.861 μm, alleviates the dependency of night vision systems on naturally occurring nocturnal sources and increases the systems performance under marginal visibility conditions. Tests with the illuminator showed a considerable improvement over the passive system.

3. Vidicon Sensors (I.R.)

One of the more significant developments in the area

of vidicon sensors (from an intrusion detection standpoint) is the development of the pyroelectric photodetector as a vidicon target. This device has the capability of imaging in the infrared. The high background level of infrared sources will saturate many pyroelectric detectors and makes the detection of moving targets difficult if not impossible. Because the pyroelectric detector is only rate sensitive, it will respond only to changes in infrared energy which is characteristics of moving targets. There are a number of techniques for creating a constantly changing temperature on the pyroelectric vidicon's target, with the most common one being the panning of the device across the scene. For security systems, however, the tube does not yet have the resolution and sensitivity necessary for imaging.

A number of pyroelectric materials have been investigated for use as a target in a vidicon tube. All usable materials have permanent dipoles that form naturally polarized microscopic domains. To utilize these materials, the target must be poled which involves applying a large electrical field across the element while elevating its temperature. The resulting element responds to a temperature change by the formation of a charge on its insulated surface. The charge pattern remains intact until it is converted into an electron current by a scanning electrical beam. The current variation as the electron beam scans the surface is the desired video signal.

A paper by Watton, et. al.[28] describes the performance of a television camera using a one-inch pyroelectric vidicon. The results of tests made on the camera are compared with an analysis which attempts to identify the factors which limit the performance of the system.

To modulate the incoming radiation two modes are considered: chopping the radiation and panning the camera. The target in the tube is a 1.8 cm diameter thin slice of TGS. Since the pyroelectric signal can be of either polarity, depending on whether the temperature of the target is rising or falling, it is necessary to provide a positive bias-current or pedestal current. The electron beam is used to generate the pedestal current by ionizing a residue of gas bled into the tube before seal-off.

To measure the minimum resoluable temperature (MRT) for the image tube, a black body bar pattern is used as a target. Measurement of the MRT is made by varying the black-body temperature until the bar pattern is just discernible above the noise on an oscilloscope display. The threshold temperature is recorded over a range of spatial frequencies. Tests showed that with the camera in a panning mode, scene temperature differences of 0.2°C could be detected. The author concludes that compared with conventional systems using arrays of cooled photoconductive detectors, the pyroelectric camera should offer a reduction in cost and complexity and

in particular dispenses with the requirement for cooling the detector element.

Singer[29] gives references on other techniques to generate the pedestal in the pyroelectric vidicon. The problem with ionized gas (see above) is the added noise injected into the signal path. An alternate approach is to use a tube with a hard vacuum and pulse the cathode negatively during the flyback time. With this pedestal generation technique, a tube is possible that has a low noise, a lifetime of 1500 hours and sells for about $4,000 in small quantities.

To improve resolution and sensitivity in pyroelectric vidicons it is necessary to:

(1) Find a material that has a maximum pyroelectric coefficient.

(2) Find a target that can be made thin. The thinner the target, the lower the thermal capacity and less thermal energy is required to produce a suitable charge for a readable signal.

(3) Find a target with low thermal diffusivity. If the heat generated by the target spreads out, the image tends to spread out and blur (defocus).

(4) Find a target material with a fast time constant. This is needed to expedite the extraction of information. The time constant is set by the capacitance of the target and the series resistance of the electron beam.

A paper related to these detectors was published by Martens in 1974[30]. This paper analyzes the temperature response function of an idealized thin-film thermal detector including losses due to radiation and conduction into the adjacent medium. In the paper, different thin-film image converters are compared.

A paper which relates to the application of video type sensors is authored by Matsunaga[31]. The author reports on a multi video sensor which is used to monitor the output of surveillance cameras. The problem with closed circuit television systems is that operators are needed to watch one or more monitors at all times. This can become very tedious or strenuous, depending on the number of monitors. The electronic surveillance system discussed produces an alarm only when some abnormal condition is detected.

A letter by H.A.H. Boot[32] describes an image tube based on the electron-mirror principle. The tube with a triglycine sulphate (TGS) pyroelectric target was developed for operation in

the 8-14 μm wavelength region. This sensitivity is comparable with that of a pyroelectric vidicon system, but power consumption is considerably less. Spatial definition exceeds that of the vidicon and is less microphonic.

A paper by F. Schwarz(33) discusses the design and application of a wide field, passive, infrared intrusion detector. The detector which cannot be classified as an imaging device can sense a human in a room having sides of 6.1 m (20 ft.) x 7.6 m (25 ft.). The field of view for the sensor extends 70° horizontally and 70° vertically. When a person enters the field of view, pulses are generated which are electrically separated from background signals.

The advantages listed by the author are:

- Because the system is completely passive, there are no beams of light or sound that can be detected by an intruder.
- There are no moving parts to wear out.
- Installation is simple. Five wires are needed to connect the sensor head to the electronics unit.
- False alarms are minimized by signal processing.
- Unit is immune to false alarms produced by targets outside the sensing area.

The detector used in this unit is an evaporated thermopile. It can be mass produced with techniques similar to those used in semiconductor technology using photo-etched masks and jigs through which the metals making up the detector elements are vacuum deposited. The detector reported on here is made up of 10 columns of junctions. The detectivity of the detector is reported as about 1×10^8 (cm $Hz^{1/2}$/watt) and can operate over the range of -12°C (10°F) to 68° (155°F). With the sensitivity specified above, a person moving within the field of view at a range of 9 m (30 ft.) will generate a signal which is about 10 times larger than the system's noise. With properly set thresholds, a false alarm rate of one in two years is reported. The author concludes his paper with a discussion regarding the possibility of a sophisticated intruder using ingenious methods to spoof or neutralize the intrusion detector. His data and discussion regarding this aspect of the device ends with the conclusion that the probability is extremely remote that an intruder could evade setting off the alarm by walking behind a shield (e.g., a large piece of cardboard considered to be at room temperature).

A passive infrared motion detector sold by the Edwards Company is very similar to the Barnes instrument discussed by Schwartz. The Edwards device also has a field of view 70° x 70° and will protect

a room 7.6 m (25 ft.) x 7.6 m (25 ft.) x 3.0 m (10 ft.). The power consumption is 2 VA (max.).

Osborne[34] describes a long-range infrared intruder alarm which is resistant to false triggering. The passive detector with a range of up to 305 m (1000 ft.) has a low false-alarm rate because it responds only to moving targets. A ferroelectric bolometer with room temperature Curie point responds to infrared radiation at wavelengths of 2 to 15 μm. A reticle in front of the infrared sensor provides sensitivity to movement. When an intruder moves across the field of view, the reticle chops the incoming radiation and thus modulates a 2 kHz square-wave carrier, produced by a multivibrator and a pair of field-effect transistors. The chopping frequency is between 0 and 25 Hz depending upon the angular speed of the source across the field.

The prototypes built weigh an average of 1.1 kg (2.5 lbs.) each, including internal rechargeable batteries and a charger. Two 12 volt batteries in series provide 8 mA for about 26 hours before recharging. A complete schematic and description is given in the article.

E. Pressure-Seismic

Most of the energy imparted to the ground by a moving vehicle or target propagates through the earth in the form of seismic waves. As the seismic wave moves through the earth, it generates a moving stress distribution and a changing particle velocity distribution. That is at some point away from the source, the particles in the earth move relative to each other. Most seismic sensors detect this state of stress by responding to the motion around them.

At the surface of the earth, the particle motion of a seismic disturbance tends to be the greatest. At this air-surface interface, accelerometers and geophones can be used advantageously. To sense the compressive stress signals (pressure signals) a sensor should be buried for best detection.

The movement of a stealthy walker is difficult to detect by using surface detection devices. A better solution is to use a buried sensor which responds to stress signals. A sensor of this type could be a buried fluid filled line. Either way, a pressure sensor may be applied directly, or indirectly by using a compliant diaphragm, one side of which is exposed to the pressure to convert a disturbance to a displacement motion or to diaphragm strains. With this background a few selected papers devoted to developments in pressure transducer technology will be discussed.

A paper by Brosh[35] describes the development of miniature pressure transducers for use in wind tunnel models. The ability to manufacture pressure sensors in sizes from 6.4 mm down to 0.8 mm diameter was attained by the application of solid state technology to the building of pressure transducers. This paper describes the design considerations, the construction and the characteristics of the sensors. The maximum pressure for the transducer is 25 psi with a natural frequency of 125 kHz. The output is 3 mV/psi with a 5 volt excitation. Data presented shows that the transducer is flat from dc to 20 kHz.

A novel pressure transducer is described by Margerum, et al.[36]. In this design, fiber optic pressure transducers with outside diameters of 3.2 mm and 4.8 mm were built and tested. In one concept tested, two optical glass fiber bundles were used. One bundle transmits light to the inner surface of a diaphragm. Reflected light is collected and transmitted by the output fiber bundle to a photometer. The output light flux becomes a measure of the pressure. The light source and sensor may be located remotely with respect to each other, and the electronics can be separated from the sensor. The optical fiber pressure transducer should be, according to the authors, less expensive to produce than either the strain gage or piezoelectric transducer and may be less temperature sensitive.

A second concept investigated employs modulations of laser power by use of a mirror attached to the pressure diaphragm. The mirror forms part of an optical cavity and displacement of the mirror by one half a wavelength causes one cycle of modulation of laser power.

For the fiber optic pressure transducer, a linear response was obtained. Test results concerning dynamic response and temperature sensitivity were inconclusive. Concept of the laser transducer was shown but the output is inherently digital and a problem with an ambiguity in counts must be solved.

Giles[37] reports on a miniature pressure transducer which uses a silicon diaphragm. In this article the transducing element is a minute circular diaphragm of single-crystal N-type silicon. The diaphragm has a diameter of about 1 mm and is an integral part of a substrate acting as a clamp ring. For measuring pressures, the diaphragm contains four small strain gauges which are configured as a Wheatstone bridge. The advantage of the monolithic construction is that it dispenses with the difficult and expensive process of mounting and tensioning an extremely thin diaphragm on a separate clamp ring.

The miniaturization of pressure transducers offers various advantages in measurement techniques. The first is improved frequency response. The authors state that they have made transducers that respond up to 100 kHz. In structural terms, the single-crystal material is more rugged. It can withstand high temperatures (up to 500°C) and is chemically not very reactive.

The limits for the measuring range of the pressure transducers can be varied between 1 atm and 100 atm. Within these limits, the sensitivity is the same. The signal sensitivity is affected by temperature but can be kept low by means of a suitable compensating device. The full-scale deflection is 20 mV per volt applied to the bridge for full-scale deflection.

Castle[38] discussed efforts to develop a temperature compensated silicon strain transducer. His transducer is similar to that reported by Giles (see above). He shows how, with the addition of a simple three resistor network, the device can be compensated such that the temperature coefficient of sensitivity is reduced to less than 0.01% per °C.

Cheney[39] is the author of another paper discussing the performance and economic advantages offered by a diffused semiconductor strain gage when used in pressure transducers. The paper reiterates some of the points emphasized by the previous authors discussed above. Cheney discusses the construction of such a device to produce excellent long-term stability and compensation techniques to produce temperature performance equivalent to wire or foil strain gage transducers. Automated compensation including laser resistor trimming is also discussed in this paper.

IV. CONCLUSIONS AND RECOMMENDATIONS

Section III has discussed selected papers which report on devices which offer promise or have improved existing detection techniques. An attempt has been made to show the state-of-the-art improvements in materials and/or materials processing and fabrication techniques. Where available, data has been presented on sensitivity, bandwidth, power consumption, cost and ruggedness. In most cases, not all of these parameters were given with respect to the transducing device.

In this techniques study, new transduction phenomena which heretofore have not been applied towards intrusion technology were also searched for. In this area, no new mechanisms were found which could be recommended for development.

The scope of the work as outlined at the beginning was limited to the conversion of phenomena to output signals. The subsequent conditioning or electronic processing of that signal is the subject of other studies and for that reason, intrusion detection systems either in existence or suggested have not been reported here. In recommending devices, a decision cannot be made on which detection system is best, but which is best for a specific application. One sensor may be best for perimeter protection and another for indoor areas. For practical applications, the target detection capability and the reliability of the sensor to reject false alarms must be compatible with the protected assets, installation site and manpower support. In this respect an acceptable sensor must meet or exceed surveillance capabilities and must have an operational maintenance requirement which is compatible with normal manpower support.

Based on the relative merits of several different transducer concepts according to the security system application criteria mentioned above, a number of promising transducer improvements have been identified. Table IV lists the selected techniques that were found to have potential for transducer applications for intrusion detectors. Table IV also includes several transducer application concepts and techniques not previously discussed but which, on the basis of current information, hold high potential for successful applicability in security systems. These techniques, as well as those identified in the previous studies, are annotated under Remarks to give better clarification as to their projected use or value.

Table V lists several selected transducers which have been proven as useful for intrusion detection applications but merit further development efforts. All devices listed here are available as commercially produced devices.

TABLE IV
SUMMARY DESCRIPTION OF PROMISING TRANSDUCERS AND CONCEPTS

Transducer, Device	Operation		Application		Coverage				Remarks
	Active	Passive	Indoor	Outdoor	Point	Line	Area	Volume	
Photodiode/Phototransistor IR Det.		x	x	x		x	x	x	Line silhouette sensor concept
Pyroelectric Film IR Det.		x	x	x		x	x	x	Mosaic imager or line silhouette sensor
CCD/CID IR Det.		x	x	x		x	x	x	Mosaic imager
Flux Gate Magnetometer		x	x	x	x				Line array of point sensors
Magnetic Gradient Vehicle Det.	x			x	x				Advantage is ease of installation
PVF_2 Film Microphone		x	x	x			x	x	Could be used in conventional application
Piezojunction Microphone		x	x	x			x	x	Identified for simplicity and low cost
IR Beam Interrupt •Pyroelectric Film Sensor	x		x	x		x			Active line silhouette sensor

TABLE V
SUMMARY OF AVAILABLE DEVICES MERITING FURTHER DEVELOPMENT

Transducer, Device	Operation		Application		Coverage				Remarks
	Active	Passive	Indoor	Outdoor	Point	Line	Area	Volume	
Image Intensifier	x		x	x		x	x	x	Used with companion imagers
Electret Microphone		x	x	x			x	x	Now used in conventional applications
RF Doppler Motion Detector	x		x	x			x	x	Now available commercially
RF Beam Interrupt	x		x	x		x			Now in use - may be used in combination with other sensors

In presenting this generalized data on promising techniques no attempt has been made to rank these concepts in terms of their value or potential contributions to security system technology. To do so would require a knowledge of the specific application. One device which must be mentioned, however, is the PVF_2 pyroelectric film infrared sensors which can be used as low-cost, non-cooled, thermal imager. A low resolution infrared imager has been designed and constructed to show the concept and is discussed in a companion document to this one. With more research and development applied towards the fabrication of high sensitivity, multi-element film detectors, it should be possible to design a high resolution, sensitive detector with imaging qualities rivaling the high cost, vacuum tube IR pyroelectric detector mosaics. This type of pyroelectric detector also has piezoelectric properties and as such has potential as a multi-mode acoustic and infrared detector.

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